ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Noise
Session 3pNSc: Joint Poster Session on Noise and Architectural Acoustics (Poster Session)

3pNSc20. Study of the acoustic of Jean Nouvel `s Auditorium 400, at the Museum Reina Sofia in Madrid
Emiliano Del Cerro* and Silvia Mª Ortiz

*Corresponding author's address: Universidad Alfonso X el Sabio, Madrid, 28691, Madrid, Spain, ecerresc@uax.es

The Auditorio 400 is one of the buildings that make up the National Art Museum Reina Sofia in Madrid. It is the work of renowned French architect Jean Nouvel. This space was designed to accommodate primarily chamber music concerts but now can be considered as a multi-purpose venue. This hall hosts events with different content: acts with the voice as main sound source as conferences, seminars etc. and concerts with music from diverse styles, classical, contemporary, avant-garde and electro acoustic music. This versatility assumes that the acoustic conditions required for the different uses of Auditorio 400 must be diverse and special depending on the sound source, in order to achieve the adequate sound quality for the various events that are held there. This paper presents the study of the acoustics of the Auditorium 400, analyzing various parameters for evaluating the sound quality of the room, highlighting the worst areas of listening, the reasons for the existence of such areas and the description of improvements to be made to ensure that the enclosure meets the expectations in a hall of its relevance.

Published by the Acoustical Society of America through the American Institute of Physics
1. INTRODUCTION

The Auditorio 400 is a space designed by Jean Nouvel, the renowned French architect winner of the Pritzker Prize in 2008. It is located in the National Museum Reina Sofia Art Center in Madrid. The auditorium, as shown in Figure 1, is a compound which is characterized by the curved surfaces of the roof, the rounded corners, the reduced height of the ceiling in the back rows of audience and by the predominance of the flat surfaces and the absence of dispersive elements. The entire surface of the walls and roof are constructed with the same material substantially reflective. The only exception is the "acoustic viewers" where the audiovisual control room is situated. The floor area of both the audience and the stage is made of jatoba wood, reddish wood that harmonizes with the predominant colors in the room. The acoustic in the auditorium is not as correct and homogeneous as desired, because of the geometry of the hall.

![Auditorio 400 at National Museum Reina Sofia Art Center.](image)

**FIGURE 1.** Auditorio 400 at National Museum Reina Sofia Art Center. Photography by José Luis Municio

In addition, it should be noted that it is a multi-purpose room, and depending on the event held, it can be used for transmission of speech or music, which implies some kind of versatility in the auditorium acoustic requirements.

This paper aims to prove, through a series of measurements and computer simulations, deficiencies in the acoustics properties of sound diffusion, detecting the worst areas of listening, the reasons for that, and therefore, the proposals for improvements, focusing our first study option from the electroacoustic point of view.

2. FIRST MEASUREMENTS AND SIMULATIONS

The different subjective opinions on the acoustics of the Auditorio 400 led to make some initial measurements focused on two essential parameters to assess the acoustics of a room: the reverberation time and the sound pressure level.

- The reverberation time should be adequate depending on the intended use of the local, so it is necessary to make a good design of architectural and decorative elements for the reverberation time suits the type of message: word or different styles of music.
- The sound pressure level measured at multiple points can establish: the dark areas of the room where the sound is muffled, the live areas where there is a reinforcement of the sound and areas where singular effects can appear as a result of sound vibration modes and room geometry. In recent years, the evaluation of the sound pressure levels is becoming one aspect to take into account, as acoustic studies by Ando, Y. [1] and Fujii, K. [2] about analysis of rooms corroborate.
Besides measurements, it was performed simulations of these two parameters with the computer program EASE, the reason was to verify the consistency of data between the “in situ” measurements and the data collected with the simulation. In this way, it was confirmed the reliability of the program, and in consequence, we could proceed to perform simulations of various designs and thereby choose the optimal solution.

2.1 REVERBERATION TIME RESULTS

Figure 2 shows the reverberation time in function of the frequency, the measured and simulated, the green one by Sabine's formula, and the violet one by the Eyring’s formula. The most significant differences are found at low frequencies. The reason can be found in the facts that formulas of Sabine, W. and Eyring, C. start from diffuse sound field conditions which ignore aspects of wave theory associated with the vibration modes.

![Figure 2](image)

**FIGURE 2.** Reverberation time in function of frequency, “red” measured, “green” simulated by Sabine's formula, and “violet” simulated by Eyring’s formula.

The average reverberation time measured in the chamber is 1.84 sec, while that the same parameter obtained in the simulation according with Sabine is 1.99 sec and according with Eyring is 1.87 sec. From the analysis of the results we can say that there is concordance between the data obtained in the measurements and the data obtained in the simulations, especially for the case where simulation is performed from the Eyring’s formula, which takes account of absorption coefficients of each area instead of the mean absorption coefficient of the enclosure as indicated Sabine's formula.

2.2 PRESSURE LEVEL RESULTS

The Auditorio 400 has speakers, some fixed and others that can be moved around. In order to study the distribution of pressure levels in the room, a series of analysis were realized based on the activation different sound sources. This paper presents the results of the configuration that is considered to provide more relevant results, the one in which two speakers were functioning in the central stage and with the sound reinforcement speakers arranged around the audience, as in a "crown", as shown in Figure 3.a). The collected data were the values of sound pressure level in the whole band and in the more representative third octave: 100Hz-fundamental frequency of the male voice, 200Hz-fundamental frequency of the female voice, 400Hz-key frequency for musical reference, 1000Hz-key frequency for acoustic measurements, 3150Hz-key frequency to evaluating the "musical presence" and 10000Hz-the frequency where we find lots of harmonics.
FIGURE 3. a) Disposition of speakers to measure the pressure level in Auditorio 400. b) Color code associated with each level of pressure. c) Total sound pressure level throughout the audible band, in dB. d) Sound pressure level in third octave band of 100 Hz. e) Sound pressure level in the third octave band of 200 Hz. f) Sound pressure in the third octave band of 400 Hz. g) Sound pressure level in the third octave band of 1000 Hz. h) Sound pressure level in the third octave band of 3150 Hz. i) Sound pressure level in the third band 10000 Hz octave, in the left the measured left and at the right side the simulated.

The data obtained from the simulation and measurements allow the following notes:

- In this situation, no data collection performed in the stage area, because the speaker layout, focused audience area, determines that the most significant pressure levels appear in the audience section.
- The layout of sound pressure levels, expressed in dB, throughout the whole audible band, is very similar between the measurement data and the simulation data. It should be noted that the sound pressure levels obtained with the simulation have values slightly higher, 1 or 2 dB, compared to those values obtained as measured data in the Auditorio 400. This is especially true in the vicinity of the speakers that conforms the "crown" situation.
- The frequency analysis in the simulation has a remarkable uniformity across the floor of the enclosure. This does not occur in measurements because the speaker layout, specifically the sound sources that are located on the opposing side walls, can cause variations in sound pressure levels. Constructive and destructive interferences produce high and low sound pressure levels, a phenomenon that is not contemplated by EASE. This aspect is reflected particularly in the low frequency range.
- To conclude this section, we can say that in view of the similarity between the results obtained with the measurements and simulation program, EASE shows adequate reliability for an acoustic study of Auditorio 400.

3. SIMULATION OF OTHER PARAMETERS

Beside reverberation time and sound pressure level as a function of frequency, other parameters are often very useful to evaluate the sound quality of the Auditorio 400. This article presents some of these parameters by simulation study. The parameters considered more decisive to define the acoustics characteristics of the room are: the clarity of the word, C50; the clarity of the music, C80, the speech intelligibility index, STI; and the loudspeaker overlap.
The study of these four parameters allows several comments:

- Figure 4 shows the physical layout of some of the most significant parameters in room acoustics with associated statistical values as a percentage, average, maximum and minimum.

- C50 index. In order to understand correctly the spoken message, the C50 index, as stated by Renkus-Heinz [3] accepted values, if the room is very reverberant, must be above 5dB. Nevertheless, this value is, in reality, too low. Carrion, A. [4] enounces that in an area with normal reverberation time, values above 0dB represent good intelligibility in rooms with a similar size as Auditorio 400. Accordingly, the clarity of the word in the vicinity of the sound sources are correct, except in the first few rows of audience and in the neighborhood of the corridors where the value obtained is far away from the objectives.

- C80 index. There are different opinions about the optimal rate C80 for concert halls: Barron, M. [5] suggests that this index varies between -2dB and 2dB, Reichardt, W. [6] states that the values of C80 should be positive, while Lehman, P. [7] considers the index must be higher than 3dB. Considering all these views Arau, H. [8] reaches a compromise, setting variation margins for concert hall: -2dB < C80 < 4dB and for theaters: C80 > 6dB. Finally, we must say that Beranek, L. [9] provides musical clarity should be in the range of 1dB to 4dB for unoccupied rooms. Accordingly, the hall presents problems of music clarity. There are some unacceptably high values and some undesired low values: in the back rows of the auditorium and in some areas near the speakers, the C80 values are higher than recommendations explained above; and, by other hand, on the lateral sides of the front rows of audience, the hall shows a C80 with very low values.

- STI index. This parameter measures the degree of speech intelligibility. It values go from 0 (completely unintelligible message) to 1 (perfect intelligibility). According to ISO 9921:2004 [10] a very good intelligibility implies that STI has values between 0.6 and 0.75. At the Auditorio 400, the central part of the audience area, an area that concentrates most of the public, does not reach the numbers recommended by the ISO normative.

- The overlap between the radiation beams of several speakers may cause interference, and in consequence, produces reinforcements and attenuation in the sound pressure level. The central area of the Auditorio 400 would also be harmed because at this point many signals from speakers converge causing constructive and destructive interferences that would alter the sound emitted by the speakers.
4. ELECTROACOUSTIC IMPROVEMENTS

This section will discuss a series of proposals for improvements to the acoustics of the venue, "playing" only with speakers of the enclosure, with their location, orientation, speaker type, level, delay, etc. These proposals will try that the sound beams cover the audience area, without causing large differences in sound pressure level, and also, that the beams radiations of the speakers do not intersect each one, we must take care of delays in order that the perceived sound source look like that it comes from the desired zone. For the study of these options, we simulated a series of different configurations of sound sources. The results are presented below with recommended options for speech and music. We must take into account, nevertheless, that a noticeable acoustic change cannot be achieved without significant modifications of absorbent parameters in the characteristics of the room.

4.1 SOLUTION FOR THE SPOKEN MESSAGE

Two speakers are activated symmetrically located on stage. Figure 5 shows the position of two speakers, and the values of the acoustic parameters tested throughout the whole frequency band:

![Figure 5: Location plan of the sound sources. Layout and statistical values of the acoustic parameters: Total sound pressure level throughout the audible band, in dB, Clarity of speech, C50, Clarity of music, C80, Index of speech intelligibility, STI.](image)

This design option allows the following notes:

- The results are quite favorable, getting enough approximation to the acoustic indices values recommended in the case of transmission of the word.
- The pressure level in dB presents higher values near the stage, because the sound sources are located in this area. It is important to say that the difference from the last row is not excessive.
- The STI index remains at similar values to the situation discussed above, because the absorption of the room is unchanged.
- The C50 improves significantly, except the last row lateral sides, which is not very problematic because these areas are small.
- The C80 reaches the recommended value in almost any location of the room.
- This option is suitable for voice because it uses only a few speakers so that the overlap and interferences between waves are minimal which produce a good clarity in the oral message.
- In view of these remarks it would be think that this would be a relatively valid solution, but it is not, because, when in some music performances, especial vocal effects were required, the Auditorio 400 requires larger number of speakers, and some problems appear in the hall.

4.2 SOLUTION FOR MUSIC

The variety of musical works performed in the Auditorio 400 leads to the conclusion that you cannot define a single speaker valid configuration for every type of music. In this paper we present two options that offer good results for many compositions.
4.2.1 First option

We try to improve the acoustic of the room in terms of sonic richness and sound effects, and for this reason we activate four speakers of the crown in the back section of the enclosure, as well we maintain four loudspeaker in the stage area. The display is show in Figure 6 a).

![Figure 6](image)

**FIGURE 6.** a) Location plan of the sound sources. Layout and statistical values of the acoustic parameters: b) Total sound pressure level throughout the audible band, in dB  c) Clarity of speech, C50. d) Clarity of music, C80. e) Index of speech intelligibility, STI. f) Loudspeaker overlaps.

The simulation results lead to the following comment:

- The sound pressure level in dB in the room increases its value, because the number of sources has been increased. This configuration may be required by some musicians depending on the work performed.
- The average value in C50 is slightly above the target. There are quite problematic areas such as those located above the second horizontal hallway.
- The C80 is among the objectives in virtually every sampled point.
- The STI has unfavorable values at the same area that the C50. This is logical because the two indices are related to the transmission of oral message.
- There is some loudspeaker overlaps, being the most conflicting areas the last rows of the section A3 and the first rows of section A5. The worst values of other parameters coincide also in these areas of the hall.

4.2.2 Second option

The acoustic conditions in the central area of the Auditorio 400 are the most problematic, according with the data analyzed in the first option for the music. In order to try to improve the acoustics conditions in that area we include a suspended ceiling speaker facing this troubled area. The display is shown at Figure 7.a).

![Figure 7](image)

**FIGURE 7.** a) Location plan of the sound sources. Layout and statistical values of the acoustic parameters: b) Total sound pressure level throughout the audible band, in dB  c) Clarity of speech, C50. d) Clarity of music, C80. e) Index of speech intelligibility, STI. f) Loudspeaker overlaps.
The most important aspects of this speaker configuration are:

- The pressure level in dB has been increased slightly and the values have been homogenized over the hall, compared with the first choice for music.
- The clarity of the word, the main problem of the room, has been improved in the area, but the average value in the enclosure is a bit away from the targets and variation range of the index C50 has been increased slightly.
- The index C80, clarity of music, maintains the values still within the limits marked as recommended. Nevertheless, at some point, this index surpasses minimally these recommended values.
- The speech intelligibility, assessed from the STI, takes very similar values to those obtained in previous proposals. In this option, it is remarkable that the STI values get a bit more uniformity than above option (figure 6.e), reducing the range of variation of the index.
- With reference to loudspeakers overlap, the worst area is in the last rows of the auditorium localized mainly in the central area of these rows, but in general, the overlapping is reduced from the previous case (figure 6.f).

5. CONCLUSIONS

The final conclusions that can be obtained with all the data collected and simulated on the current configuration of the Auditorio 400, as well as for some improvements proposals can be summarized in the following points:

- The reverberation of the room is excessive, resulting in problems of intelligibility. This high reverberation, together with the shape of the room and the number and arrangement of the speakers, cause also lack of clarity of the word.
- The frequency distribution of reverberation is not advisable. There are very high values in the central region of the spectrum. This causes that the midrange reverberation time and the warmth index are inadequate.
- The prevalence of flat surfaces, the geometry, the absorption of the hall, and the lack of dispersion generate that the sound diffusion is not the correct one and therefore some acoustic parameters, such as clarity in music and in speech, are not uniform in the Auditorium 400.
- All of these statements about the problems of the auditorium are consistent with those described by Christensen, C. L. [11] on the influence of the sound pressure level and the sound diffusion over the acoustic quality in an auditorium.
- Electroacoustic changes do not represent a substantial improvement, since they do not involve changes in the absorption of the room, and in consequence, the main problem at the Auditorium 400 continues being the same: excessive reverberation time.
- The electroacoustic improvements, although they do not introduce substantial changes, they allow enhance some parameters, and therefore, make better acoustics conditions in the room.
- The election of electroacoustic changes, instead of absorption modifications or introduction of variable acoustic systems, has the lowest economic investment. In addition, it does not require the introduction of changes in the architectural structure. Beside, under the aesthetic point of view, this option does not transform the style of the hall. This is an important consideration given the prestige of the creator of the work.

6. REFERENCES


